

## **Eddy Resolving Global Ocean Prediction including Tides**

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### **LONG-TERM GOALS**

Use the HYbrid Coordinate Ocean Model (HYCOM) with tides, dynamic sea ice, and data assimilation in an eddy-resolving, fully global ocean prediction system with  $1/25^\circ$  horizontal resolution that will run in real time at the Naval Oceanographic Office (NAVOCEANO) starting in 2012. The model will include shallow water and provide boundary conditions to finer resolution coastal models that may use HYCOM or a different model.

### **OBJECTIVES**

To develop, evaluate, and investigate the dynamics of  $1/25^\circ$  global HYCOM (HYbrid Coordinate Ocean Model) with tides coupled to CICE (the Los Alamos sea ice model) with atmospheric forcing only, with data assimilation via NCODA (NRL Coupled Ocean Data Assimilation), and in forecast mode. Also to incorporate advances in dynamics and physics from the science community into the HYCOM established and maintained within the Navy.

### **APPROACH**

Traditional ocean models use a single coordinate type to represent the vertical, but no single approach is optimal for the global ocean. Isopycnal (density tracking) layers are best in the deep stratified ocean, pressure levels (nearly fixed depths) provide high vertical resolution in the mixed layer, and  $\sigma$ -levels (terrain-following) are often the best choice in coastal regions. The generalized vertical coordinate in HYCOM allows a combination of all three types (and others), and it dynamically chooses the optimal distribution at every time step via the layered continuity equation. HYCOM use a C-grid, has scalable, portable computer codes that run efficiently on available DoD High Performance Computing (HPC) platforms, and has a data assimilation capability.

Global HYCOM with  $1/12^\circ$  horizontal resolution at the equator ( $\sim 7$  km at mid-latitudes) is the ocean model component of the eddy-resolving nowcast/forecast system currently running in real time in the operational queue on the Cray XT5 at the Naval Oceanographic Office (NAVOCEANO). It provides nowcasts and forecasts of the three dimensional global ocean environment. HYCOM is coupled to the Los Alamos CICE sea-ice model (Hunke and Lipscomb, 2004) via the Earth System Modeling

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Framework (ESMF) (Hill et al., 2004), although currently for Arctic-only configurations. Coupling between the ocean and ice models more properly accounts for the momentum, heat and salt fluxes at the ocean/ice interface. The final component of the nowcast/forecast system is the NRL Coupled Ocean Data Assimilation (NCODA) which is a multivariate optimal interpolation scheme that assimilates surface observations from satellites, including altimeter and Multi-Channel Sea Surface Temperature (MCSST) data, sea ice concentration and also profile data such as XBTs (expendable bathythermographs), CTDs (conductivity temperature depth) and ARGO floats (Cummings, 2005). By combining these observations via data assimilation and using the dynamical interpolation skill of the model, the three dimensional ocean state can be accurately nowcast and forecast.

The principal goal of this project is to perform the necessary R&D to prepare to provide a next-generation ocean nowcast/forecast system with real time depiction of the three-dimensional global ocean state at fine resolution ( $1/25^\circ$  on the equator, 3.5 km at mid-latitudes, and 2 km in the Arctic). A major sub-goal of this effort is to test new capabilities in the existing  $1/12^\circ$  global HYCOM nowcast/forecast system and to transition some of these capabilities to NAVOCEANO in the  $1/12^\circ$  system, and others in the  $1/25^\circ$  global system. The new capabilities support (1) increased nowcast and forecast skill, the latter out to 30 days in many deep water regions, including regions of high Navy interest such as the Western Pacific and the Arabian Sea/Gulf of Oman, (2) boundary conditions for coastal models in very shallow, and (3) external and internal tides, the latter will initially be tested at  $1/12^\circ$ , to minimize computational cost, but will transition to NAVOCEANO only in the  $1/25^\circ$  system because at this resolution it will replace regional models with tides (all these will greatly benefit from the increase to  $1/25^\circ$  resolution). In addition to the NRL core tasking covered here, this effort will collaborate with a core team of similar size at FSU COAPS, with other parties interested in HYCOM development, and ONR field programs to test and validate the model in different regions and different regimes. Demonstrated advancements in HYCOM numerics and physics from all sources will be incorporated through this project.

## **WORK COMPLETED**

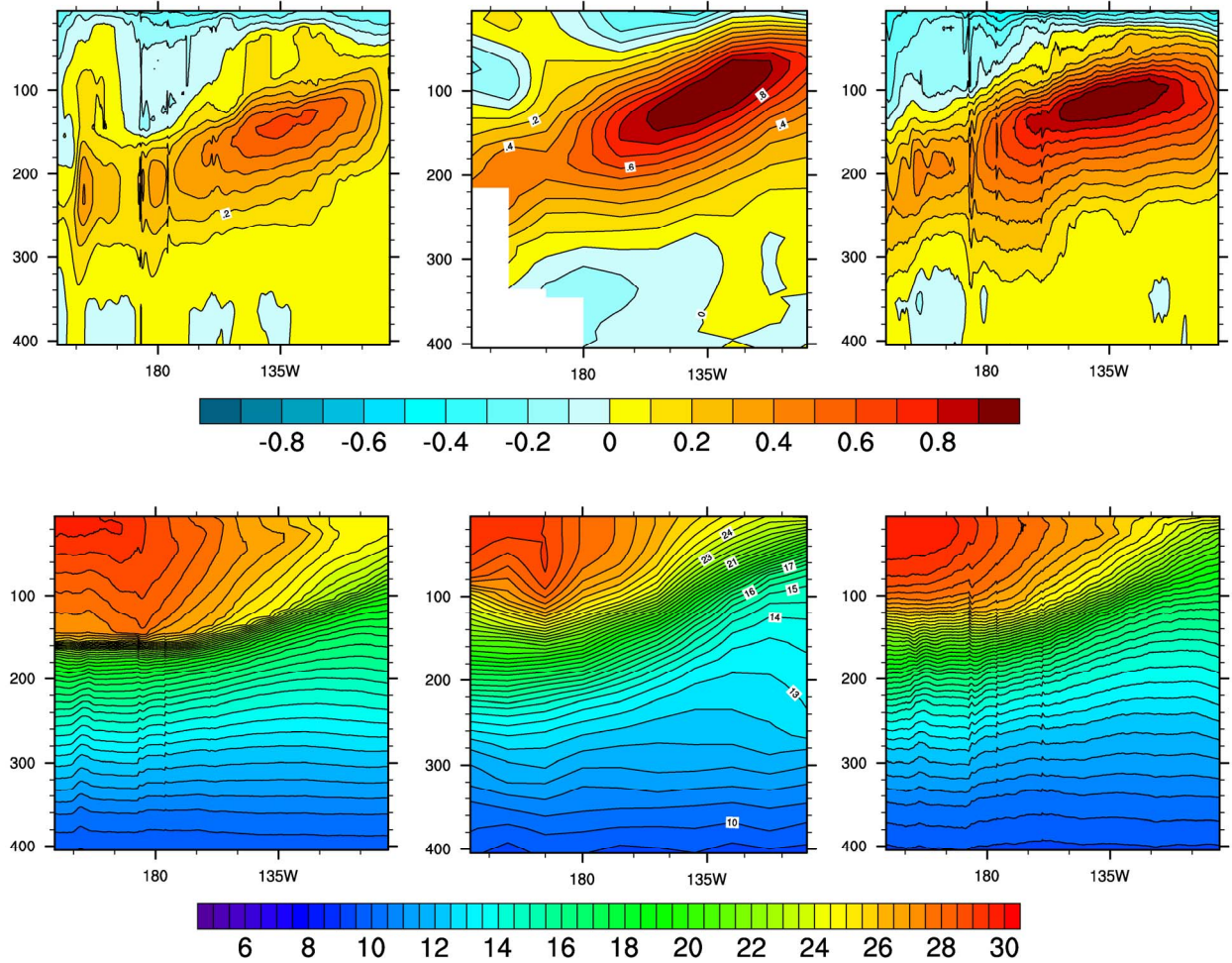
HYCOM version 2.2.18 was made available on the HYCOM web site. This includes numerous improvements over version 2.1. The most significant of these is an improved vertical remapper, *hybgen*, which was implemented in FY08 but first used extensively this year.

The first  $.04^\circ$  global HYCOM simulations (3.5 km resolution at mid-latitudes) were run a total of 8.7 model years in collaboration with other projects, starting on 12 January 2009. This is the highest resolution ever for a global ocean model with high vertical resolution (2x finer horizontal grid spacing). It was run at NAVOCEANO using an HPC Challenge grant of computer time from the DoD HPC Modernization Program. For comparison, near twin  $.08^\circ$  global HYCOM simulations were also integrated, including the same climatological 6-hourly atmospheric forcing (derived from the European Centre for Medium-Range Weather Forecasts 40-year reanalysis, ERA-40, with wind speed scaled using a monthly climatology from the QuikScat scatterometer; Kara et al., 2009) and bottom topography derived from the same  $.04^\circ$  data set. However, the  $.08^\circ$  topography was subjected to numerous hand edits in past years, mainly in shallow water and particularly to straits and sill depths, while the  $.04^\circ$  global topography has received relatively few edits, mainly in FY09 to the Philippine and Indonesian Archipelagos.

The coupled CICE+HYCOM (sea-ice and ocean) model has been upgraded to the latest version of each model component (CICE 4.0 and HYCOM 2.2.18). It has been tested globally at  $0.72^\circ$  resolution, but the primary focus this year was a  $3.5\text{ km}$  Arctic cap domain that is an exact copy of the  $1/12^\circ$  degree global tri-pole grid north of  $40^\circ\text{N}$ . It is one-way off-line nested inside global HYCOM at  $40^\circ\text{N}$ . Both non-assimilative and assimilative (NCODA) cases have been run. The latter to support validation of the  $1/12^\circ$  degree global system's sea ice capability

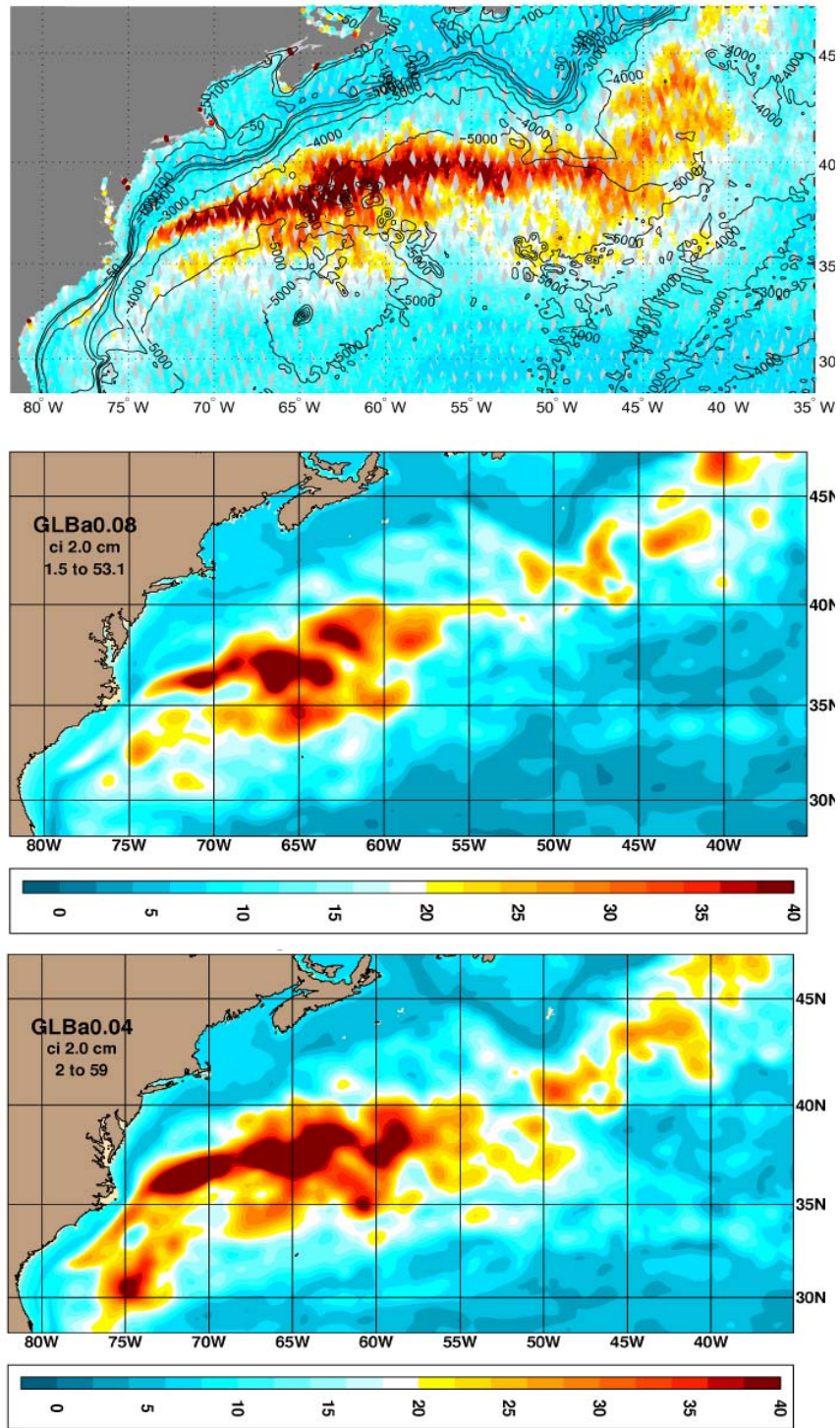
## RESULTS

Figure 1 illustrates the difference that model improvements have made to the simulation of the Equatorial Pacific. The largest factor in the improvement is the use of higher-order vertical remapping in HYCOM version 2.2 vs 1<sup>st</sup> order remapping in version 2.1. The strength of the equatorial undercurrent is now more realistic and the thermocline is better defined. However, there is still too little upwelling in the Eastern Equatorial Pacific.

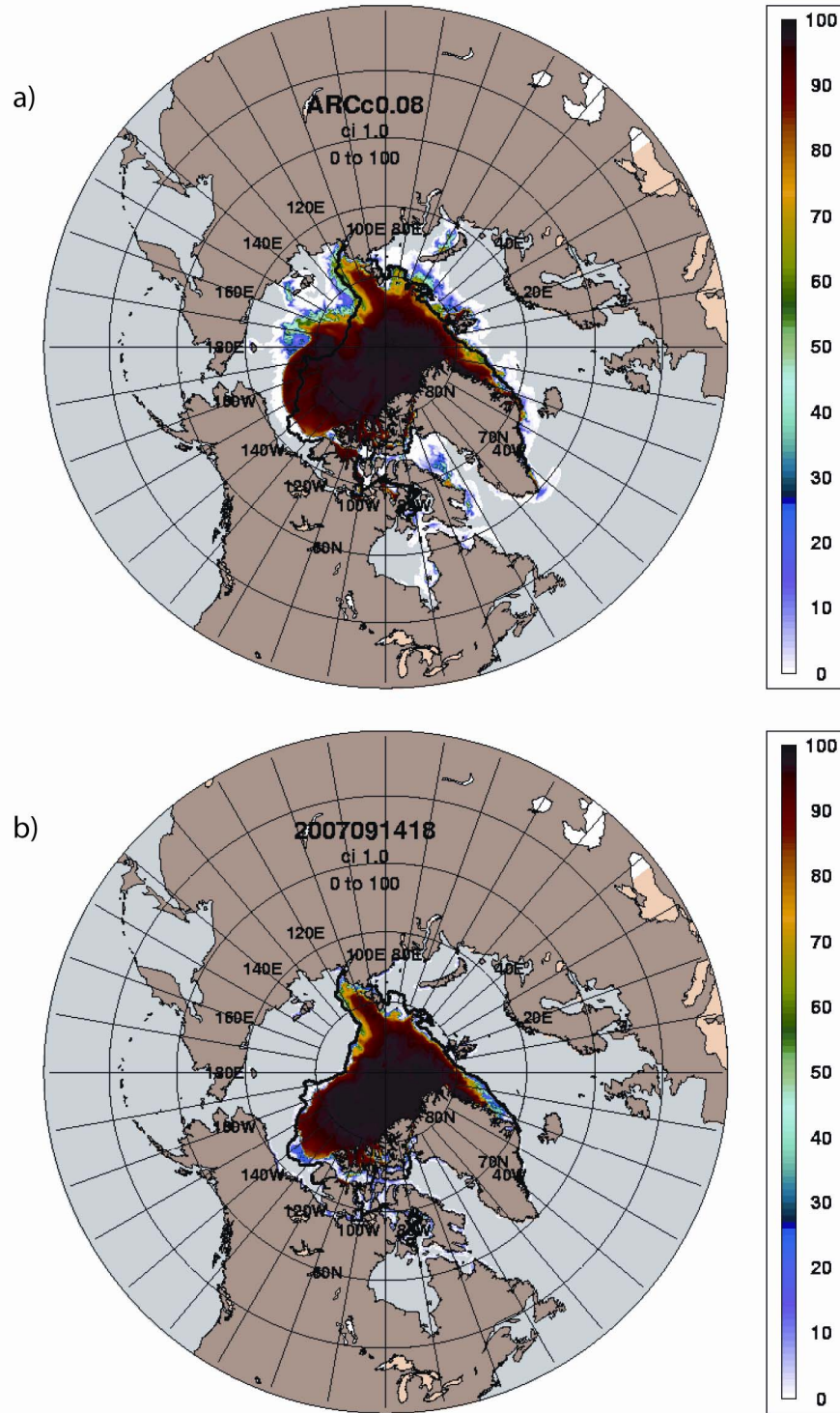


**Figure 2.** Along-equator annual-mean sub-surface velocity (top) and temperature (bottom) in the Pacific Ocean from (left to right): (a) a  $1/12^\circ$  global simulation using HYCOM 2.1, (b) observations at the TAO array (Johnson et al, 2007), and (c) a  $1/25^\circ$  global simulation using HYCOM 2.2.





**Figure 2. Zooms of the Gulf Stream region, all using the same color scale in cm. (a) Quasi-contemporaneous along-track RMS SSH variability from satellite altimeter data in four orbits overlaid on topographic contours (depth in m). The tracks are overlaid in the following order from top to bottom: (1) Envisat, (2) GFO, (3) Jason-1, and (4) Topex interleaved. (b,c) RMS SSH variability over model year 3 from non-assimilative (b) 1/12° and (c) 1/25° global HYCOM simulations.**



**Figure 3.** Sea ice contentration in September 14, 2007 from two 3.5 km Arctic cap HYCOM+CICE cases atmospherically forced by NOGAPS : (a) non-assimilative (b) with NCODA assimilation. Heavy black line is the National Ice Center's daily ice edge location. This data is not assimilated into the ice model.

Figure 2 compares the sea surface height variability in the Gulf Stream region from identical twin simulations at  $1/12^\circ$  and  $1/25^\circ$  after just three model years with along-track variability from four satellite altimeters. The Gulf Stream greatly benefits from higher resolution and the Stream is already penetrating further with more realistic variability at  $1/25^\circ$ .

Figure 3 compares twin simulations of the coupled HYCOM and CICE Arctic cap system. The heavy black line is the National Ice Center's daily ice edge location for this day. This data is not assimilated into the ice model, and so provides an independent indication of how well the model is performing. The non-assimilative simulation is already relatively accurate (particularly since the NIC's ice edge probably represents about 15% concentration), but its area of high concentration is too high. Adding SSMI ice concentration via NCODA significantly improves the comparison to the ice edge, although there are areas where ice is underestimated.

## **IMPACT/APPLICATIONS**

The  $1/25^\circ$  (3.5 km mid-latitude) resolution, first used in some FY09 global HYCOM simulations, is the highest so far for a global ocean model with high vertical resolution. A global ocean prediction system, based on  $1/25^\circ$  global HYCOM with tides, is planned for real-time operation starting in 2012. At this resolution, a global ocean prediction system can directly provide boundary conditions to nested relocatable models with  $\sim 1$  km resolution anywhere in the world, a goal for operational ocean prediction at NAVOCEANO. Internal tides and other internal waves can have a large impact on acoustic propagation and transmission loss (Chin-Bing et al., 2003, Warn-Varnas et al., 2003, 2007), which in turn significantly impacts Navy anti-submarine warfare and surveillance capabilities. At present, regional and coastal models often include tidal forcing but internal tides are not included in their open boundary conditions. By including tidal forcing and assimilation in a fully 3-D global ocean model we will provide an internal tide capability everywhere, and allow nested models to include internal tides at their open boundaries.

## **TRANSITIONS**

The  $1/12^\circ$  global HYCOM system is running in real time, and was transitioned to NAVOCEANO at the end of FY08 with operational testing is planned in FY10. It is receiving 6.4 SPAWAR funding (see below) for evaluation/validation.

## **RELATED PROJECTS**

Partnering projects at NRL include 6.1 Global Remote Littoral Forcing via Deep Water Pathways, the 6.1 PhilEx DRI project Flow through the straits of the Philippine Archipelago simulated by global HYCOM and EAS NCOM, 6.1 Dynamics of the Indonesian Throughflow (ITF) and its remote impact, 6.2 Full Column Mixing for Numerical Ocean Models, 6.3 Battlespace Environments Institute – ESMF for Atmospheric-Ice-Ocean Coupling and Component Interoperability, 6.4 Large Scale Ocean Modeling, 6.4 Ocean Data Assimilation, and 6.4 Ice Modeling Assimilation from NPOESS. The computational effort is strongly supported by DoD HPC Challenge and NRL non-challenge grants of computer time. In FY09  $1/25^\circ$  and  $1/12^\circ$  global HYCOM ran under a new FY09-11 DoD HPC Challenge grant.

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